CHECKER-BOARD OPTICAL CROSS-CONNECT

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to optical cross-connects, and particularly to three-dimensional optical cross-connects.

2. Technical Background

Over the past several decades, fiber optic technology has transformed the telecommunications industry. A decade ago, network designs included relatively low-speed transceiver electronics at each end of a communications link. Light signals were switched by being converted into electrical signals. The electrical signals were switched using electronic switches, and converted back again into light signals. The bandwidth of electronic switching equipment is in the Gigahertz range. On the other hand, the bandwidth of single mode fiber is in the Terahertz range. As the demand for bandwidth increased, network designers have sought ways to exploit the bandwidth in the 1550nm region. Thus began the development of optically transparent switching fabrics.

Currently, optical designers are considering free-space plane-to-plane optical interconnects, often referred to as three-dimensional optical cross-connects (3D OXCs). 3D OXCs have the potential to make large scale N x N switching a reality. However, there are several drawbacks to large scale N x N switching fabrics. The fundamental limit on the minimum pitch associated with the beam steering arrays and collimator arrays is limited by the required diameter of the optical beam. The minimum separation between beams required to limit cross-talk will ultimately limit the path density of the free-space interconnect. Likewise, the maximum size of the collimator and beam steering arrays will be limited by the batch processing techniques used for fabrication.

Another factor limiting the size of switching arrays relates to the angular deflection required to fully access all of the pixels in a particular array. This is illustrated by the 3D OXC is shown in Figure 1. OXC 100 includes tile 110 disposed in one plane and tile 120 aligned in a plane-to-plane relationship with tile 110. Tile 110 includes collimator array 102 and beam steering array 104. Tile 120 includes beam steering array 106 and collimator array 108. Light signal LS is directed into OXC 100

via collimator 1020. Pixel 1060 reflects light signal LS toward pixel 1040. Finally, light signal LS is directed out of OXC 100 via collimator 1080. In the example depicted in Figure 1, the maximum angular deflection of light signal LS is shown. Clearly, as the physical dimensions of array 100 are increased, the required angular deflection to access all of the pixels in the array is also increased.

In one approach that is being considered, optical designers are tiling switching arrays to increase the physical dimensions of the optical cross-connect. As shown in Figure 2, a second OXC 300 is layered over OXC 100. OXC 300 includes tile 310 disposed in one plane and tile 320 aligned plane-to-plane with tile 310. In Figure 2, the maximum angular deflection of LS2 is shown. It is important to note that the maximum angular deflection of the composite switch (LS2) is much larger than the maximum angular deflection of LS1. As a result, this limits the potential size of an array. One way of reducing the magnitude of the maximum angular deflection is to increase the path length by increasing the separation distance "Z." However, this is not viable because this will increase the required beam size, decreasing the path density through the interconnect accordingly. Finally, if the path length must be increased to accommodate additional tile layers, the system would no longer be scalable.

What is needed is a tiling scheme to effectively increase the port count of the interconnect without increasing the angular deflection required to access all of the pixels in the switch.

Summary of the Invention

The present invention addresses the needs identified above. The present invention includes a tiling scheme that effectively increases the port count of a three-dimensional optical cross-connect switch without increasing the angular deflection required to access all of the pixels in the switch.

One aspect of the present invention is a three-dimensional optical cross-connect switch. The switch includes a first optical switching array having a first tile disposed in a first plane, and a second tile aligned plane-to-plane with the first tile in a second plane. The first tile includes a first collimator array disposed adjacent to a first beam steering array. The second tile includes a second collimator array disposed adjacent to a second beam steering array. The first optical switching array is characterized by a first array maximum deflection angle. The switch also includes a second optical

switching array having a third tile disposed in the first plane, and a fourth tile aligned plane-to-plane with the third tile in the second plane. The third tile includes a third collimator array disposed adjacent to a third beam steering array. The fourth tile includes a fourth collimator array disposed adjacent to a fourth beam steering array. The maximum deflection angle of the switch is less than or equal to the first array maximum deflection angle.

In another aspect, the present invention includes a three-dimensional optical cross-connect switch. The switch includes a first optical switching array and a second optical switching array. The first optical switching array includes a first tile having a first collimator array disposed adjacent to a first beam steering array, and a second tile having a second collimator array disposed adjacent to a second beam steering array. The second collimator array is aligned plane-to-plane with the first beam steering array. The second beam steering array is aligned plane-to-plane with the first collimator array. The second optical switching array includes a third tile having a third collimator array disposed adjacent to a third beam steering array, and a fourth tile having a fourth collimator array disposed adjacent to a fourth beam steering array. The fourth collimator array is aligned plane-to-plane with the third beam steering array. The fourth beam steering array is aligned plane-to-plane with the third collimator array. The third beam steering array is disposed adjacent the first collimator array to form a checkerboard pattern.

In another aspect, the present invention includes a three-dimensional optical cross-connect switch. The switch has a first optical switching array including a first tile disposed in a first plane, and a second tile disposed in a second plane parallel to the first plane. The first tile includes a first collimator array disposed adjacent to a first beam steering array. The second tile includes a second collimator array disposed adjacent to a second beam steering array. The first beam steering array and the second beam steering array each have N-steerable pixel elements. The first optical switching array is characterized by an array maximum deflection angle that is required to access each pixel in the first optical switching array. A second optical switching array is coupled to the first optical switching array. The second optical switching array includes a third tile

disposed in the first plane and a fourth tile disposed in the second plane. The third tile includes a third collimator array disposed adjacent to a third beam steering array. The fourth tile includes a fourth collimator array disposed adjacent to a fourth beam steering array. The third beam steering array and the fourth beam steering array each have N-steerable pixel elements. The maximum deflection angle of the switch that is required to access each pixel in the cross-connect switch is less than or equal to the first array maximum deflection angle.

In another aspect, the present invention includes a method for expanding a switching capacity of a three-dimensional optical cross-connect switch. The method includes providing a first optical switching array. The first optical switching array includes a first tile disposed in a first plane and a second tile aligned plane-to-plane with the first tile in a second plane. The first tile includes a first collimator array disposed adjacent to a first beam steering array. The second tile includes a second collimator array disposed adjacent to a second beam steering array. The first optical switching array is characterized by an array maximum deflection angle. A second optical switching array is provided that includes a third tile disposed in the first plane, and a fourth tile aligned plane-to-plane with the third tile in the second plane. The third tile includes a third collimator array disposed adjacent to a third beam steering array. The fourth tile includes a fourth collimator array disposed adjacent to the fourth beam steering array. The first optical switching array is coupled to the second optical switching array. The maximum deflection angle of the three-dimensional optical cross-connect switch is less than or equal to the array maximum deflection angle.

In another aspect, the present invention includes a method for expanding a switching capacity of a three-dimensional optical cross-connect switch. The method includes providing a first optical switching array. The first optical switching array includes a first tile having a first collimator array disposed adjacent to a first beam steering array, and a second tile having a second collimator array disposed adjacent to a second beam steering array. The second collimator array is aligned plane-to-plane with the first beam steering array. The second beam steering array is aligned plane-to-plane with the first collimator array. The first optical switching array is characterized by a first array maximum deflection angle. A second optical switching array is provided that includes a third tile and a fourth tile. The third tile has a third collimator array disposed adjacent to a third beam steering array. The fourth tile has a fourth collimator

array disposed adjacent to a fourth beam steering array. The fourth collimator array is aligned plane-to-plane with the third beam steering array, and the fourth beam steering array is aligned plane-to-plane with the third collimator array. The third beam steering array is disposed adjacent the first collimator array in a checkerboard pattern. The first optical switching array is coupled to the second optical switching array. The maximum deflection angle of the three-dimensional optical cross-connect switch is less than or equal to the array maximum deflection angle.

In another aspect, the present invention includes a method for switching optical signals in a three-dimensional optical cross-connect switch. The switch includes a first optical switching array having a first tile disposed in a first plane, and a second tile aligned plane-to-plane with the first tile in a second plane. The first tile includes a first collimator array disposed adjacent to a first beam steering array. The second tile includes a second collimator array disposed adjacent to a second beam steering array. The first optical switching array is characterized by an array maximum deflection angle. The method includes providing a second optical switching array having a third tile disposed in the first plane, and a fourth tile aligned plane-to-plane with the third tile in the second plane. The third tile includes a third collimator array disposed adjacent to a third beam steering array. The fourth tile includes a fourth collimator array disposed adjacent to the fourth beam steering array. The first optical switching array is coupled to the second optical switching array such that the maximum deflection angle of the three-dimensional optical cross-connect switch is less than or equal to the array maximum deflection angle. The light signal is directed into the first collimator array causing the light signal to propagate toward the second plane

Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

It is to be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended

to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate various embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

Brief Description of the Drawings

Figure 1 is a block diagram of a three-dimensional optical cross-connect having one tiled switching array;

Figure 2 is a block diagram of a three-dimensional optical cross-connect having two tiled switching array;

Figure 3 is a block diagram of the checker-board three-dimensional optical cross-connect architecture in accordance with the present invention;

Figure 4 is a chart comparing the performance of the checker-board three-dimensional optical cross-connect architecture depicted in Figure 3 with the three-dimensional optical cross-connect depicted in Figure 2;

Figure 5 is a detail view of the gimbaled pixel employed in the beam steering arrays of the present invention;

Figure 6 is a detail view of a pixel mirror element employed in the gimbaled pixel shown in Figure 5;

Figure 7 and Figure 8 are representative examples of an N x N optical cross-connect in accordance with the present invention; and

Figure 9 and Figure 10 are representative examples of an N x N optical cross-connect with optical shared protection in accordance with the present invention

Detailed Description

Reference will now be made in detail to the present exemplary embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts. An exemplary embodiment of the three-dimensional optical cross-connect switch of the present invention is shown in Figure 1, and is designated generally throughout by reference numeral 10.

In accordance with the invention, the present invention for a three-dimensional optical cross-connect switch includes a first optical switching array having a first tile disposed in a first plane, and a second tile aligned plane-to-plane with the first tile in a second plane. The first tile includes a first collimator array disposed adjacent to a first beam steering array. The second tile includes a second collimator array disposed adjacent to a second beam steering array. The first optical switching array is characterized by a first array maximum deflection angle that is required to access all of the pixels in the first array. A second optical switching array includes a third tile disposed in the first plane, and a fourth tile aligned plane-to-plane with the third tile in the second plane. The third tile includes a third collimator array disposed adjacent to a third beam steering array. The fourth tile including a fourth collimator array disposed adjacent to a fourth beam steering array. The switch maximum deflection angle is less than or equal to the first array maximum deflection angle. Thus, the tiling scheme of the present invention effectively increases the port count of a three-dimensional optical cross-connect switch without increasing the angular deflection required to access all of the pixels in the switch.

As embodied herein, and depicted in Figure 3, a block diagram of checker-board 3D OXC 10 in accordance with the present invention is disclosed. OXC 10 includes switching array 100 coupled to switching array 300. Switching array 100 includes tile 110 and tile 120, aligned in a plane-to-plane relationship with tile 110. Tile 110 includes collimator array 12 disposed adjacent to beam steering array 14. Tile 120 includes collimator array 18 disposed adjacent to beam steering array 16. Collimator array 12 is aligned with beam steering array 16, and collimator array 18 is aligned with beam steering array 14. Switching array 300 includes tile 310 and tile 320, aligned in a plane-to-plane relationship with tile 310. Tile 310 includes collimator array 20 disposed adjacent to beam steering array 22. Tile 320 includes collimator array 24 disposed adjacent to beam steering array 26. Collimator array 22 is aligned with beam steering array 26, whereas collimator array 24 is aligned with beam steering array 20.

As shown, collimator array 12, collimator array 22, beam steering array 14, and beam steering array 20 are arranged in a checker-board pattern. Likewise, collimator

array 18, collimator array 24, beam steering array 16, and beam steering array 26 are also arranged in a checker-board pattern. As shown by comparing the path of light signal LS1 to the path of light signal LS2, there is no increase in the overall maximum angular deflection of OXC 10 vis á vis the maximum angular deflection of switching array 100. Thus, the checker-board tiling scheme of the present invention effectively increases the port count without increasing the angular deflection required to access all of the beam steering pixels.

Figure 4 compares the performance of checker-board 3D OXC 10 depicted in Figure 3 to 3D OXC 200, depicted in Figure 2. Plot line 402 shows the maximum angle ratio as a function of the physical dimensions of OXC 10. Plot line 404 shows the maximum angle of OXC 200 (Figure 2) as a function of the physical dimensions of OXC 200. Plot line 406 shows the maximum angle of OXC 10 (Figure 3) as a function of the physical dimensions of OXC 10. It is clear from Figure 4 that for z/d ratios of 10 or greater, the tiling scheme used in Figure 2 requires a 25% growth in the angular deflection of the beam steering arrays. On the other hand, the checker-board architecture depicted in Figure 3 requires no growth in angular deflection because of the inherent symmetry of the design. Thus, system designers can upgrade from a single tier system to the system depicted in Figure 3 without changing the geometry of the device because the maximum angle is the same; whereas system designers cannot upgrade from the system depicted in Figure 1 to the system depicted in Figure 2 without changing the geometry of the overall module design. In other words, the migration from Figure 1 to Figure 2 requires the replacement of the system of Figure 1 with the system of Figure 2 because the geometries are necessarily different. On the other hand, the present invention provides system designers with the flexibility of expanding the system of Figure 1 to arrive at the system depicted in Figure 3, without having to replace the Figure 1 system. This results in significant cost savings.

As embodied herein and depicted in Figure 5, a detail view of the gimbaled pixel assembly 500 employed in the beam steering arrays of the present invention is disclosed. In one embodiment, the beam steering arrays include 10 x 10 = 100 pixel assemblies 500. Obviously, this means that the collimator arrays are also 10 x 10 arrays as well. One of ordinary skill in the art will recognize that the size of these arrays is variable, dependent on the factors discussed above in the Technical Background.

Assembly 500 includes reflective pixel element 502. Pixel 502 is coupled to frame member 508 via beam 504 and beam 506. Beam 504 and beam 506 allow pixel element 502 to rotate around the y-axis. Frame member 508 is coupled to substrate 514 via beam 510 and beam 512. Beam 510 and beam 512 allow frame member 508 to rotate about the x-axis. Thus, pixel element 502 is steerable with 2-degrees of freedom. As shown in Figure 5, pixel assembly 500 is suspended over trench 520. An electrostatic actuator assembly (not shown) is disposed under pixel assembly 500 in trench 520. The electrostatic actuator assembly is coupled to a control system. The actuator assembly includes an electrode disposed under each beam 504, 506, 510, and 512) To cause a rotation around beam 504 and beam 506, the electrodes under beam 510 and 512 are actuated by applying an actuation voltage. To cause a rotation around beam 510 and beam 512, the electrodes under beam 504 and beam 506 are actuated by applying an actuation voltage. The beams twist when they are rotated and become springs that supply a balancing force to the applied electro-static forces. The beams also supply a return force when the applied voltage is reduced.

As embodied herein and depicted in Figure 6, a detail view of pixel element 502 employed in gimbaled pixel assembly 500 is disclosed. Pixel element 502 includes reflective surface 5022 disposed on substrate 5020. It will be apparent to those of ordinary skill in the pertinent art that modifications and variations can be made to pixel element 502 of the present invention depending on the beam size of incident light signals. For example, the side dimension "L" of pixel element 502 may range between 200μm to 1mm. The width "W" of pixel element 502 is usually below 10μm, and typically about 5μm. One of ordinary skill in the art will also recognize that pixel element 502 can be formed using a number of photolithographic techniques, such as MEMS micro-machining. In one embodiment, substrate 5020 is formed using a silicon or polysilicon material. Reflective layer 5022 is formed by depositing a layer of gold over substrate 5020.

Figure 7 and Figure 8 are representative examples of an N x N optical cross-connect in accordance with an ADD/DROP embodiment of the present invention. In Figure 7, both light signal LS1 and light signal LS 2 are cross-connected in pass-

through in array 100. In Figure 8, the ADD/DROP functionality of OXC 10 is illustrated. Light signal LS1 is cross-connected in pass-through, whereas light signal LS2 is dropped from the traffic flow of array 100, and light signal LS3 is added to the traffic flow of array 100.

Figure 9 and Figure 10 are representative examples of an N x N optical cross-connect with optical shared protection in accordance with a third embodiment of the present invention. In Figure 9, light signal LS11 and light signal LS12 comprise the west bound traffic in an optical shared protection ring environment. Light signal LS21 and light signal LS22 comprise the east bound traffic. In this example, a fault has developed in the east bound ring due to a fiber cut, a faulty switching node, or for some other reason. Light signal LS12 carries low-priority traffic. As shown in Figure 10, LS12 is disconnected. East bound light signal LS21 and east bound light signal LS22 are re-routed by beam steering array 26. LS21 and LS22 are directed toward beam steering array 14 instead of array 20. Light signal LS21 and light signal LS22 are directed out of collimator array 18 and into the west bound traffic flow. Thus, LS21 and LS 22 are re-routed around the cause of the fault in the ring.

It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.